

## 1. Spectroscopy of Ultra-Cool Dwarfs

Ultra-cool dwarfs have been defined as dwarfs with spectral types of M7 or later (Kirkpatrick, Henry, & Irwin 1997) and thus include the new L and T spectral classes. The previous IAU report on ultra-cool dwarfs in 1999 described the optical and IR spectral features that characterize these spectral types. In this report, I review the latest progress on the spectral classification of ultra-cool dwarfs, which are divided into two categories: old dwarfs in the field ( $> 1$  Gyr) and their young progenitors in the nearest star-forming regions and open clusters (1-100 Myr). Because the former are nearby and the latter are young, these two groups are relatively bright and lend themselves to discovery and detailed study. I conclude by discussing some of the major results from two recent meetings. Technically, the luminosity class of young ultra-cool objects is closer to subgiant than dwarf; nevertheless, I include them in this report on ultra-cool dwarfs.

### 1.1. The Field

Three years ago, L-type objects had been discovered in abundance ( $\sim 100$ ), while only a dozen T-type sources were known. Since then, 2MASS, SDSS, and other surveys have identified another 150 L dwarfs and 20 T dwarfs free-floating in the field (Cuby et al. 1999; Strauss et al. 1999; Kirkpatrick et al. 2000; Reid et al. 2000; Tsvetanov et al. 2000; Leggett et al. 2000; Burgasser et al. 1999, 2000b, 2002a; Hawley et al. 2002; Liu et al. 2002b). The first L and T dwarfs were discovered as companions (GD165B, Becklin & Zuckerman 1988; Gl229B, Nakajima et al. 1995), and companion searches have continued to reveal new members of these spectral classes. Ultra-cool dwarfs orbiting field stars have been found at wide angular separations through 2MASS images and followup spectroscopy by Kirkpatrick et al. (2001), Wilson et al. (2001), Gizis, Kirkpatrick, & Wilson (2001), and Burgasser et al. (2000a). Companions that are likely to be ultra-cool have appeared at small angular separations in images obtained with HST and ground-based telescopes using adaptive optics (AO) (Martín et al. 2000b; Reid et al. 2001b; Els et al. 2001; Close et al. 2002a, 2002b), some of which have been observed with newly available AO spectroscopy (Potter et al. 2002; Goto et al. 2002; Liu et al. 2002a).

Spectral classification of ultra-cool dwarfs began with optical data for M and L types (Kirkpatrick et al. 1999; Martín et al. 1999b). Classification at these types has since been developed at IR wavelengths (Reid et al. 2001a; Leggett et al. 2001; Testi et al. 2001). The numerous discoveries of ultra-cool dwarfs have produced a well-sampled spectral sequence into late L and T types, enabling the definition of spectral subclasses in the T regime (Burgasser et al. 2002a; Geballe et al. 2002). To first order, the T spectral class was originally defined by the presence of methane absorption at IR wavelengths. However, under the accepted classification schemes for L and T types, late L dwarfs exhibit methane absorption at  $3.3 \mu\text{m}$  (Noll et al. 2000), and possibly at  $2.2 \mu\text{m}$  as well (McLean et al. 2001; Nakajima, Tsuji, & Yanagisawa 2001). The temperatures below which methane absorption appears in each photometric band have been compared to theoretical predictions by Schweitzer et al. (2002). In addition to temperature, clouds are probably responsible for much of the variation in spectral features among L and T types (Burgasser et al. 2002b).

### 1.2. Open Clusters and Star-forming Regions

Searches for ultra-cool dwarfs in nearby open clusters and star-forming regions have been motivated by the fact that brown dwarfs ( $M \lesssim 0.075 M_{\odot}$ ) are brightest and warmest when they are young, which enables their detection down to very low masses. For instance, objects near the hydrogen burning mass limit have spectral types of M6-M7 when they are younger than 100 Myr, and eventually cool to mid-L types after several Gyr. In other words, a given ultra-cool spectral type corresponds to a much lower mass (by an order of magnitude) in a star-forming region than in the field.

The Pleiades open cluster (125 Myr) was the first site to prove fruitful in surveys for young ultra-cool dwarfs (Stauffer, Hamilton, & Probst 1994; Martín et al. 2000a). Members of this cluster have been found with spectral types as late as early L ( $\sim 0.035 M_{\odot}$ , Martín et al. 1998). In the last few years, the emphasis has shifted to very young associations and star-forming clusters ( $< 10$  Myr), where the brown dwarfs should be even more luminous. Free-floating ultra-cool objects have been identified with optical and IR spectroscopy toward IC 348 (Luhman 1999), Chamaeleon I (Neuhäuser & Comerón 1999; Comerón, Neuhäuser, & Kaas 2000), Ophiuchus (Luhman, Liebert, & Rieke 1997; Wilking, Greene, & Meyer 1999; Cushing, Tokunaga, & Kobayashi 2000), Taurus (Martín et al. 2001a), the Orion Nebula Cluster (Hillenbrand 1997; Lucas et al. 2001),  $\sigma$  Ori (Béjar et al. 1999; Zapatero Osorio et al. 2000; Barrado et al. 2001), and the TW Hya association (Gizis 2002). In addition, companion searches have located late-type secondaries to young stars in the Taurus star-forming region (White et al. 1999) and in the associations of Tucanae (Lowrance et al. 2000; Guenther et al. 2001) and TW Hya (Lowrance et al. 1999; Neuhäuser et al. 2000). Most of these sources are late-M ( $0.01$ - $0.1 M_{\odot}$ ), while a smaller number of L-type objects ( $0.005$ - $0.01 M_{\odot}$ ) have been found toward Orion and  $\sigma$  Ori.

I now describe the spectral features that vary between ultra-cool dwarfs in the field and their young counterparts in clusters. Over time, the processes of convection and nuclear burning deplete Li at the surfaces of young low-mass stars and brown dwarfs. This depletion occurs faster for more massive objects, resulting in a boundary between non-Li and Li objects that evolves to lower masses, and thus fainter luminosities and cooler temperatures. For instance, the Li depletion boundary is near the hydrogen burning mass limit for an age of  $\sim 100$  Myr. Stauffer, Schultz, & Kirkpatrick (1998), Barrado et al. (1999), and Stauffer et al. (1999) have used this phenomenon to estimate ages for the Pleiades (125 Myr), IC 2391 (53 Myr), and  $\alpha$  Per (90 Myr) open clusters. In star-forming clusters, ultra-cool sources are too young to have depleted their Li and thus exhibit strong absorption at  $6707 \text{ \AA}$  (Martín, Basri, & Zapatero Osorio 1999a). At M types, the presence of Li absorption can be used to distinguish young late-type members of a cluster from foreground field dwarfs. However, the time scale for Li depletion becomes longer with lower masses, so that some L-type members of the field ( $> 1$  Gyr) can exhibit Li absorption. As a result, at L types Li is not a definitive indicator of membership in a young cluster.

Because ultra-cool objects are extremely faint at optical wavelengths, the high-resolution data necessary for Li measurements are difficult to obtain. Instead, youth and membership are more easily determined with the gravity-sensitive Na I and K I absorption lines, which are stronger than Li and reside at brighter regions of the optical spectrum. At late M types, these features are weaker in members of open clusters and star-forming regions than in field dwarfs, which has been attributed to the lower surface gravities of the former (Martín, Rebolo, & Zapatero Osorio 1996; Luhman et al. 1998). However, at types later than  $\sim L0$ , these lines are difficult to use as diagnostics of youth because they become weaker and the optical flux continues to decrease. Ultra-cool field dwarfs and young sources can be differentiated at IR wavelengths, which is where these objects are most easily observed. Steam absorption at each end of the H and K bands results in a plateau in the spectra of dwarfs, while for young sources this plateau is less apparent and the spectrum is instead more sharply peaked (Lucas et al. 2001).

L-type objects found toward star-forming regions are sometimes referred to as “planetary-mass objects” (Lucas et al. 2001; Zapatero Osorio et al. 2000) because L0 corresponds roughly to the deuterium burning mass limit ( $0.013$ - $0.015 M_{\odot}$ ) for ages of  $< 10$  Myr (Burrows et al. 1997; Baraffe et al. 1998). The relationship between the L types reported by Lucas et al. (2001) from IR spectra and the standard optically-based classifications for field dwarfs is unclear, but these sources are likely to be young members of Orion because they show IR steam features that are distinctive from those of field dwarfs, and in a manner that is consistent with predicted variations with surface gravity (Allard et al. 2001). However, many of the L-type objects toward the  $\sigma$  Ori cluster lack convincing spectroscopic evidence of youth and membership in the cluster. Although the early L source found by Zapatero

Osorio et al. (1999) appears to have Na I and K I line strengths that are indicative of youth, the remaining objects are too faint ( $I > 21$ ) for such measurements. Barrado y Navascués et al. (2001) reported strong H $\alpha$  emission for some these sources, which would be evidence for youth, but most of these detections appear to have marginal significance by the spectra presented in that study. Indeed, the distinctive shape of the steam absorption bands observed for young objects in Orion by Lucas et al. (2001) is not present in the  $\sigma$  Ori objects (Martín et al. 2001b), which may indicate that the latter are foreground field dwarfs rather than cluster members.

For the spectral classification of young objects at late-M types, Luhman (1999) found that the various spectral features between 6000 and 9000 Å are best matched with averages of spectra for standard dwarfs and giants. Because some of the IR steam bands become stronger at a fixed temperature from dwarfs to young objects (Allard et al. 2001), optically-classified young sources are probably the appropriate standards when using IR spectra to measure spectral types for young late-type objects.

## References

- Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, *ApJ*, 556, 357
- Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, *A&A*, 337, 403
- Barrado y Navascués, D., Stauffer, J. R., Song, I., & Caillault, J.-P. 1999, *ApJ*, 522, L53
- Barrado y Navascués, D., Zapatero Osorio, M. R., Béjar, V. J. S., Rebolo, R., Martín, E. L., Mundt, R., & Bailer-Jones, C. A. L. 2001, *A&A*, 377, L9
- Becklin, E. E., & Zuckerman, B. 1988, *Nature*, 336, 126
- Béjar, V. J. S., Zapatero Osorio, M. R., & Rebolo, R. 1999, *ApJ*, 521, 671
- Burgasser, A. J., et al. 1999, *ApJ*, 522, L65
- Burgasser, A. J., et al. 2000a, *ApJ*, 531, L57
- Burgasser, A. J., et al. 2000b, *AJ*, 120, 1100
- Burgasser, A. J., et al. 2002a, *ApJ*, 564, 421
- Burgasser, A. J., et al. 2002b, *ApJ*, 571, 151
- Burrows, A., et al. 1997, *ApJ*, 491, 856
- Close, L. M., Potter, D., Brandner, W., Lloyd-Hart, M., Liebert, J., Burrows, A., & Siegler, N. 2002a, *ApJ*, 566, 1095
- Close, L. M., Siegler, N., Potter, D., Brandner, W., & Liebert, J. 2002b, *ApJ*, 567, L53
- Comerón, F., Neuhauser, R., & Kaas, A. A. 2000, *A&A*, 359, 269
- Cuby, J. G., Saracco, P., Moorwood, A. F. M., D’Odorico, S., Lidman, C., Comerón, F., & Spyromilio, J. 1999, *A&A*, 349, 41
- Cushing, M. C., Tokunaga, A. T., & Kobayashi, N. 2000, *AJ*, 119, 3019
- Els, S.G., Sterzik, M.F., Marchis, F., Pantin, E., Endl, M., & Kürster, M. 2001, *A&A*, 370, L1
- Geballe, T. R., et al. 2002, *ApJ*, 564, 466
- Gizis, J. E. 2002, *ApJ*, 575, 484
- Gizis, J. E., Kirkpatrick, J. D., & Wilson, J. C. 2001, *AJ*, 121, 2185
- Goto, M., et al. 2002, *ApJ*, 567, L59
- Guenther, E. W., Neuhauser, R., Huélamo, N., Brandner, W., & Alves, J. 2001, *A&A*, 365, 514
- Hawley, S. L., et al. 2002, *AJ*, 123, 3409
- Hillenbrand, L. A. 1997, *AJ*, 113, 1733
- Kirkpatrick, J. D., et al. 1999, *ApJ*, 519, 802
- Kirkpatrick, J. D., et al. 2000, *AJ*, 120, 447

- Kirkpatrick, J. D., Dahn, C. C., Monet, D. G.; Reid, I. N., Gizis, J. E., Liebert, J., & Burgasser, A. J. 2001, *AJ*, 121, 3235
- Kirkpatrick, J. D., Henry, T. J., & Irwin, M. J. 1997, *AJ*, 113, 1421
- Leggett, S. K., et al. 2000, *ApJ*, 536, L35
- Leggett, S. K., Allard, F., Geballe, T. R., Hauschildt, P. H., & Schweitzer, A. 2001, *ApJ*, 548, 908
- Liu, M. C., Fischer, D. A., Graham, J. R., Lloyd, J. P., Marcy, G. W., & Butler, R. P. 2002a, *ApJ*, 568, 107
- Liu, M. C., Wainscoat, R., Martí, E. L., Barris, B., & Tonry, J. 2002b, *ApJ*, 568, L107
- Lowrance, P. J., et al. 1999, *ApJ*, 512, L69
- Lowrance, P. J., et al. 2000, *ApJ*, 541, 390
- Lucas, P. W., Roche, P. F., Allard, F., & Hauschildt, P. H. 2001, *MNRAS*, 326, 695
- Luhman, K. L. 1999, *ApJ*, 525, 466
- Luhman, K. L., Briceño, C., Rieke, G. H., & Hartmann, L. W. 1998, *ApJ*, 493, 909
- Luhman, K. L., Liebert, J., & Rieke, G. H. 1997, *ApJ*, 489, L165
- Martín, E. L., et al. 1998, *ApJ*, 507, L41
- Martín, E. L., et al. 2000a, *ApJ*, 543, 299
- Martín, E. L., Basri, G., Zapatero Osorio, M. R. 1999a, *AJ*, 118, 1005
- Martín, E. L., Delfosse, X., Basri, G., Goldman, B., Forveille, T., & Zapatero Osorio, M. R. 1999b, *AJ*, 118, 2466
- Martín, E. L., Dougados, C., Magnier, E., Ménard, F., Magazzù, A., Cuilandre, J.-C., & Delfosse, X. 2001a, *ApJ*, 561, L195
- Martín, E. L., Koresko, C. D., Kulkarni, S. R., Lane, B. F., & Wizinowich, P. L. 2000b, *ApJ*, 529, L37
- Martín, E. L., Rebolo, R., & Zapatero Osorio, M. R. 1996, *ApJ*, 469, 706
- Martín, E. L., Zapatero Osorio, M. R., Barrado y Navascués, D., Béjar, V. J. S., & Rebolo, R. 2001b, *ApJ*, 558, L117
- McLean, I. S., Prato, L., Kim, S. S., Wilcox, M. K., Kirkpatrick, J. D., & Burgasser, A. 2001, *ApJ*, 561, L115
- Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, *Nature*, 378, 463
- Nakajima, T., Tsuji, T., & Yanagisawa, K. 2001, *ApJ*, 561, 119
- Neuhäuser, R., & Comerón, F. 1999, *A&A*, 350, 612
- Neuhäuser, R., Guenther, E. W., Petr, M. G., Brandner, W., Huélamo, N., & Alves, J. 2000, *A&A*, 360, 39
- Noll, K. S., Geballe, T. R., Leggett, S. K., & Marley, M. S. 2000, *ApJ*, 541, 75
- Potter, D., Martin, E. L., Cushing, M. C., Baudoz, P., Brandner, W., Guyon, O., & Neuhäuser, R. 2002, *ApJ*, 567, L133
- Reid, I. N., Burgasser, A. J., Cruz, K. L., Kirkpatrick, J. D., & Gizis, J. E. 2001a, *AJ*, 121, 1710
- Reid, I. N., Gizis, J. E., Kirkpatrick, J. D., & Koerner, D. W. 2001b, *AJ*, 121, 489
- Reid, I. N., et al. 2000, *AJ*, 119, 369
- Schweitzer, A., Gizis, J. E., Hauschildt, P. H., Allard, F., Howard, E. M., & Kirkpatrick, J. D. 2002, *ApJ*, 566, 435
- Stauffer, J. R., et al. 1999, *ApJ*, 527, 219
- Stauffer, J. R., Hamilton, D., & Probst, R. G. 1994, *AJ*, 108, 155
- Stauffer, J. R., Schultz, G., & Kirkpatrick, J. D. 1998, *ApJ*, 499, 199
- Strauss, M. A., et al. 1999, *ApJ*, 522, L61

- Testi, L., et al. 2001, ApJ, 552, L147
- Tsvetanov, Z. I., et al. 2000, ApJ, 531, L61
- White, R. J., Ghez, A. M., Reid, I. N., & Schultz, G. 1999, ApJ, 520, 811
- Wilking, B. A., Greene, T. P., & Meyer, M. R. 1999, AJ, 117, 469
- Wilson, J. C., Kirkpatrick, J. D., Gizis, J. E., Skrutskie, M. F., Monet, D. G., & Houck, J. R. 2001, AJ, 122, 1989
- Zapatero Osorio, M. R., Béjar, V. J. S., Martín, E. L., Rebolo, R., Barrado y Navascués, D., Bailer-Jones, C. A. L., & Mundt, R. 2000, Science, 290, 103
- Zapatero Osorio, M. R., Béjar, V. J. S., Rebolo, R., Martín, E. L., & Basri, G. 1999, ApJ, 524, L115